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New Spools for the C0 IR

BTEV / C0

- Spools – a brief overview
  - A collection of disparate components
- New spools – X1, X2, & X3
  - What we are building
- Critical components
  - Corrector magnets
- Critical components
  - HTS Leads

Spools – a brief overview

- ‘Spool piece’ –
  a collection of cryogenic, magnetic, electrical, and vacuum components necessary to the accelerator and not accommodated elsewhere…
- Components/functions include
  - Magnetic correction elements
    - Dipole, quadrupole, and sextupole correctors
      - normal and skew components in most cases
  - Current leads and bus
    - HTS and ‘conventional’ high current leads
    - Corrector leads
    - Tevatron and LHC-style bus

Spool Piece Overview

- Components/functions, cont.
  - Safety leads, 'quench stoppers'
  - Beam Position Monitors
  - Quench relief valves (1Φ,2Φ-He, N)
  - Vacuum breaks
  - Other instrumentation
    - E.g., thermometry
- Spool pieces provide cryogenic interfaces between different 'objects'
  - Standard 'Tevatron' piping to low beta quadrupole interfaces

Spool Piece Overview

- Spool piece components differ according to location
  - Corrector packages vary
  - Interfaces
  - Power leads and bus
- New spools include 3 basic designs – X1, X2, & X3 – but 5 different variants due to different components and interfaces

New Spools

- Three spool designations – X1, X2, & X3 – as viewed from corrector complement:

  X1 – V or H dipole, Sextupole, Strong Quad (slot length 1.83m)

  X2 – V & H dipoles (slot length 1.43m)

  X3 – V & H dipoles, Skew Quad – located between Q2 & Q3 (slot length 1.43m)

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New Spool Design

- Design/engineering challenges
  - Slot length, slot length, slot length
  - Multiple interfaces
    - Tevatron
    - New LHC style quadrupoles
    - *Note: Different bus sizes and splice lengths*
  - 'Left handed' & 'right handed' interconnects
  - HTS leads – LN2 plumbing
  - Corrector lead assemblies (aka "conning towers")
  - Beam Position Monitors embedded inside the vacuum break
  - Heat load requirements
  - Design to ASME code

New Spool Table

	Magnetic Elements							*Current Leads*		*Interfaces*					
Spool	**Slot Length, m**	**VD T. m**	**HD T. m**	**SQ T.m/m**	**Sx T.m/m^2**	**Q* T.m/m**	**BPM**	**HTS Leads**	**Other Leads**	**UpStr comp.**	**UpStr intf**	**UpStr bus**	**DnStr comp.**	**DnStr intf**	**DnStr bus**
X1V	1.83	0.48			450	25			3x50A + SL	Quad	Tev	Tev	Dipole	Tev	Tev
X1H	1.83		0.48		450	25			3x50A	Quad	Tev	Tev	Dipole	Tev	Tev
X2L	1.43	0.48	0.48				V&H	2x10kA	2x50A + SL	**Q5**	Mod. Tev?	Tev, LHC	Dipole	Tev	Tev
X2R	1.43	0.48	0.48				V&H	2x10kA	2 x50A	Cold bypass	Tev	Tev	**Q4**	Mod. Tev?	Tev, LHC
X3	1.43	0.48	0.48	7.5			V&H	2x10kA	3x50A + 200A	**Q3**	New	LHC	**Q2**	New	LHC
X3	1.43	0.48	0.48	7.5			V&H	2x10kA	3x50A + 200A	**Q2**	New	LHC	**Q3**	New	LHC
X2R	1.43	0.48	0.48				V&H	2x10kA	2x50A	Dipole	Tev	Tev	**Q4**	Mod. Tev?	Tev, LHC
X2L	1.43	0.48	0.48				V&H	2x10kA	2x50A + SL	**Q5**	Mod. Tev?	Tev, LHC	Dipole	Tev	Tev
X1V	1.83	0.48			450	25			3x50A	Quad	Tev	Tev	Dipole	Tev	Tev
X1H	1.83		0.48		450	25			3 x 50A + SL	Quad	Tev	Tev	Dipole	Tev	Tev

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New Spools – What are the Issues?

- Engineering complexity
  - Limited space, multiple components, stringent requirements on alignment, heat load, etc.
- Magnetic Elements
  - New corrector configurations
  - Strong quadrupole corrector
  - Dimensional constraints (see above)
- High Current Leads
  - Heat load/refrigeration limits forgo conventional Cu leads
  - HTS leads required, but 10kA leads (with LN2 cooling) are not readily available

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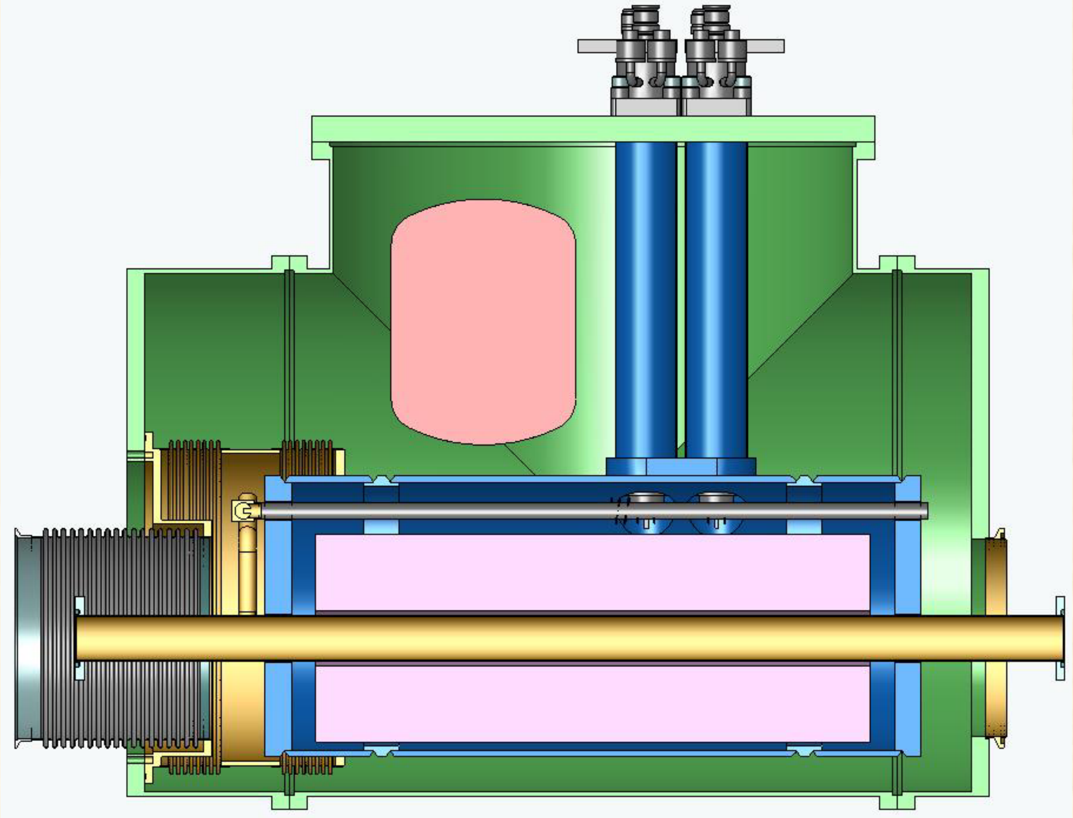
Conceptual Drawing - X2 Spool

An "in progress" view of spool components



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Conceptual Drawing - X2 Spool

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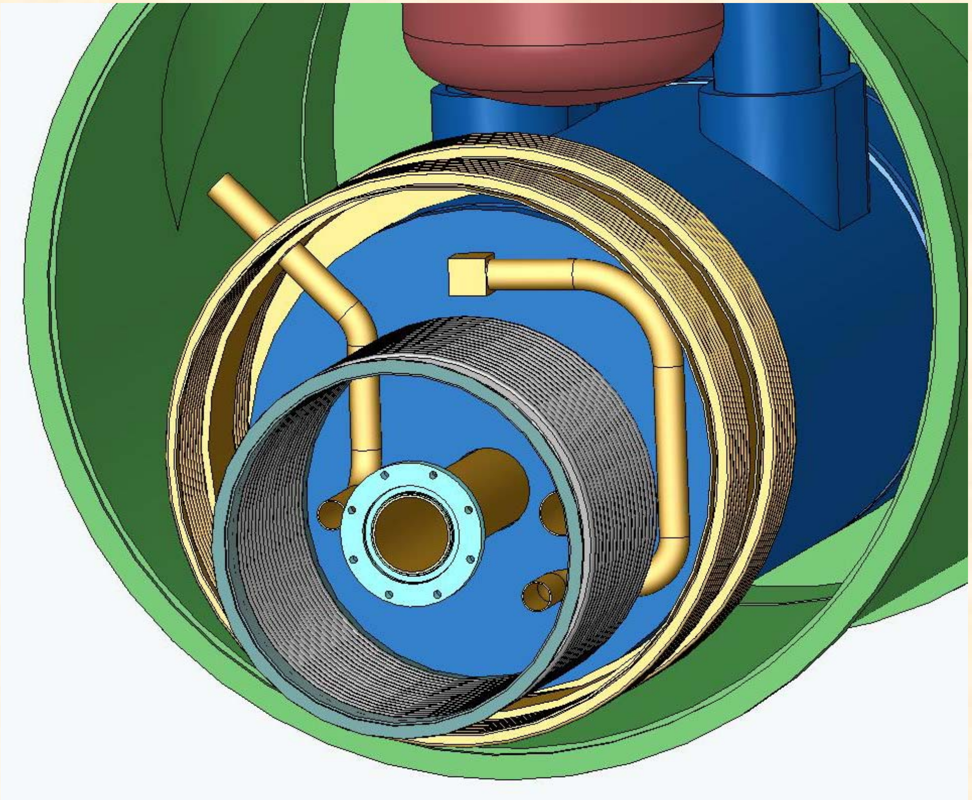
Tevatron interface end



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New Spools – Awaiting Definitions

- Corrector / corrector leads
  - All leads will be for 50A correctors
  - Number of leads depends on corrector choice and specific spool
- BPM
- Tunnel space at all new spool locations
  - In progress: details needed to determine clearances/interferences
- Bus work / splice layout for interfaces
  - determines final slot length needed
  - single phase pipe size

Corrector Magnets

- Most corrector requirements (field integrals) are the same as existing spools with the exception of the new strong quadrupole: 25T-m/m

Corrector type	Existing Correctors	C0 Requirements	units
dipole	.460	.480	T-m
quadrupole	7.5	7.5	T-m/m
Strong quadrupole	none	**25**	T-m/m
sextupole (up)	449	450	$T\text{-}m/m^2$
sextupole (down)	346	450	$T\text{-}m/m^2$
octupole	30690	none	$T\text{-}m/m^3$

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Corrector Magnets

- 10 new spools incorporating 26 corrector magnets are required
- Magnet design - two approaches
  - cos (nθ) -'traditional' approach - is the baseline design individual coils are wound for each harmonic to be corrected
  - 'Flat Coil' array is an alternative approach which provides a multi-function magnet which can be configured to provide any of the desired harmonic

cos (nθ) Design

- Strengths
  - Conventional design
  - cos(nθ) well understood
  - good field quality
  - LHC-like: conductor and experienced manufacturers exist
  - No R&D required
- Consequences
  - Different coil required for each harmonic corrected
  - Different coil packages for each spool type

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cos (nθ) coil conceptual design

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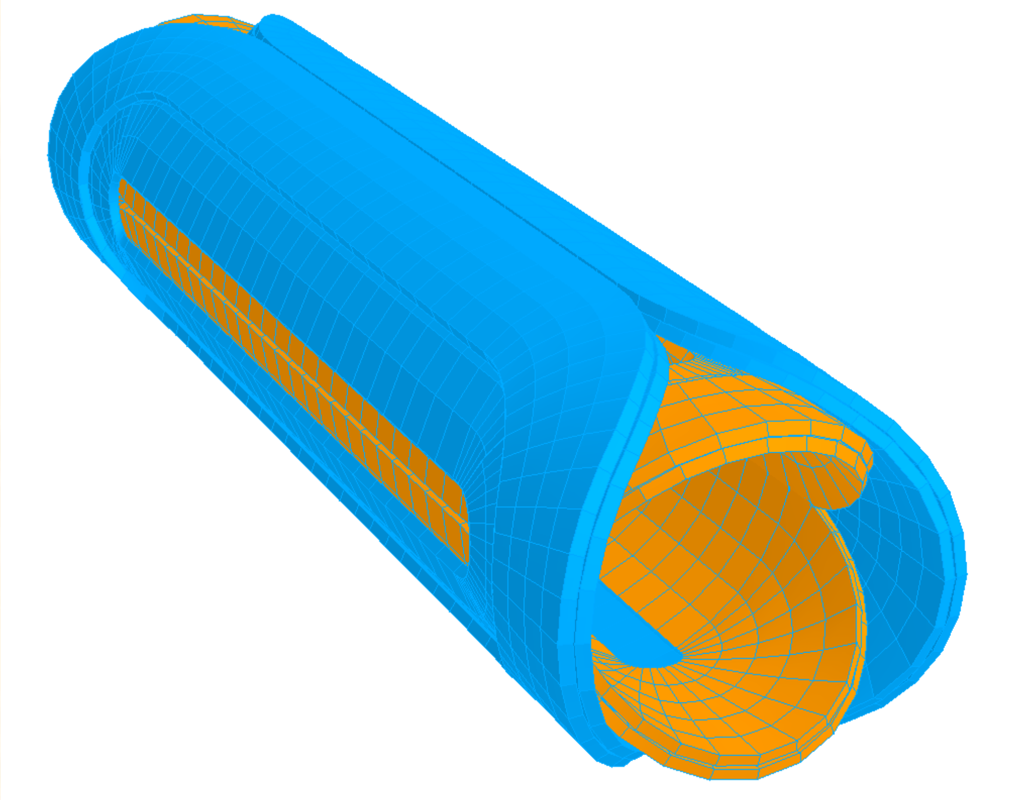
Nested dipole correctors:



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Summary of cos(nθ) Corrector Parameters

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		X2, X3 (56in) Spool Corrector Components			X1 (72in) Spool Corrector Components		
Parameter	**Unit**	**ND** *(n=0)*	**SD** *(n=0)*	**SQ** *(n=1)*	**NQ** *(n=1)*	**NS** *(n=2)*	**ND** *(n=0)*
Coil IR	*mm*	40.00	48.00	40.00	40.00	48.00	40.00
Yoke IR	*mm*	60.00		53.00	60.00		53.00
Strands/cable		10			10		
Bare strand diameter	*mm*	0.30			0.30		
Cu/nonCu ratio		2.00			2.00		
J_{nonCu}(5T, 4.2K)	A/mm^2	2750			2750		
Nominal strength	$T{\cdot}m/m^n$	0.48	0.48	7.50	25.00	450.00	0.48
Nominal current	*A*	27.2	23.6	49.0	40.0	36.6	43.0
Quench margin at nominal current in all the coils	%	54.7	58.8	38.2	40.6	42.9	39.2
Inductance	*H/m*	15.16	25.03	6.48	5.42	6.24	17.01
Stored energy at I_{nom}	*kJ/m*	5.61	6.97	7.78	4.34	4.18	15.73
Magnetic length	*m*	**0.35**	**0.35**	**0.14**	**0.68**	**0.70**	**0.20**
Physical length	*m*	**0.55**		**0.25**	**0.80**		**0.40**

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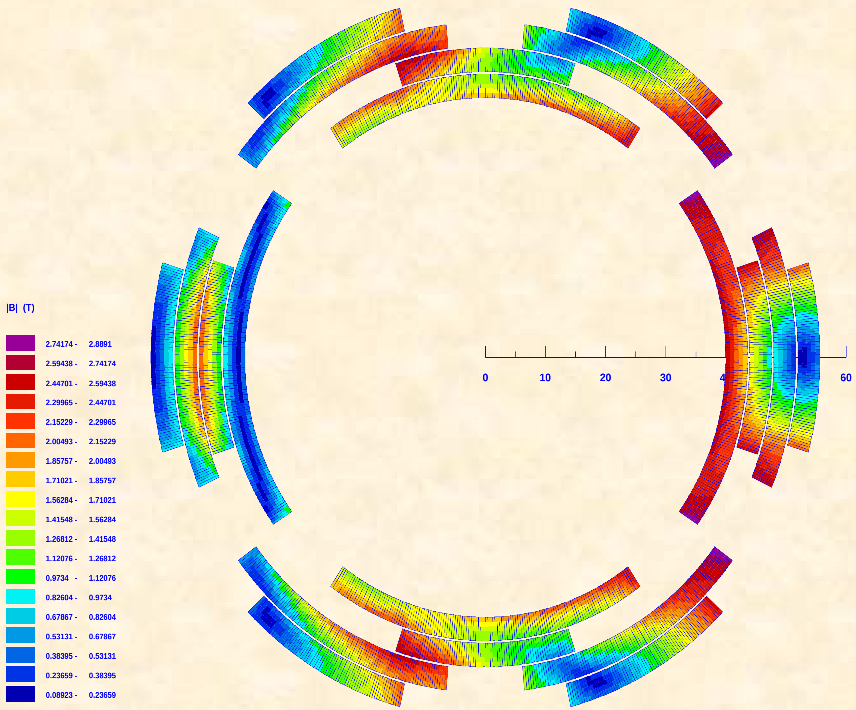
cos (nθ) calculated harmonics



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- Nested Quadrupole / Sextupole calculated harmonics

Quadrupole:

MAIN FIELD: 0.93930 NORMAL REL. MULTIPOLES (1.D-4):

b 1:	0.00000	b 2:	10000.00000	b 3:	0.00000
b 4:	0.00000	b 5:	0.00000	b 6:	0.17997
b 7:	0.00000	b 8:	0.00000	b 9:	0.00000
b10:	0.39959	b11:	0.00000	b12:	0.00000
b13:	0.00000	b14:	0.46534	b15:	0.00000
b16:	0.00000	b17:	0.00000	b18:	-0.22728

Sextupole:

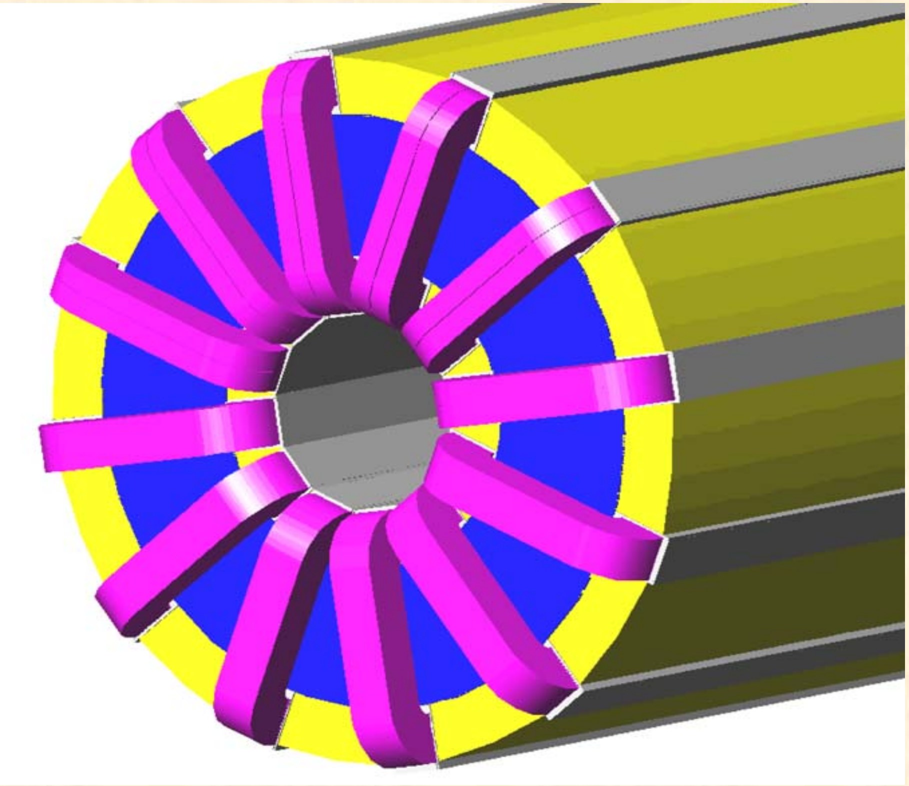
MAIN FIELD: 0.41682 NORMAL REL. MULTIPOLES (1.D-4):

b 1:	0.00000	b 2:	0.00000	b 3:	10000.00000
b 4:	0.00000	b 5:	0.00000	b 6:	0.00000
b 7:	0.00000	b 8:	0.00000	b 9:	-0.09100
b10:	0.00000	b11:	0.00000	b12:	0.00000
b13:	0.00000	b14:	0.00000	b15:	-0.17912
b16:	0.00000	b17:	0.00000	b18:	0.00000

Note: 2-dim. Body fields only;
ends will add harmonics (e.g.sextupole)
which will need compensation in body

'Flat coil' Design

Conceptual drawing of flat coil array



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Flat Coil Array Magnetic Design

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- A combined function magnetic field
  - 12 identical race-track coils distributed with an angular separation of 30^{o}
  - Minimum number necessary to provide the required dipole, quadrupole and sextupole fields
  - Rectangular coil cross-section was chosen to simplify the winding
  - In the most general case, each coil is powered separately
- Algebraic solutions to various current/harmonic configurations

Flat coil concept

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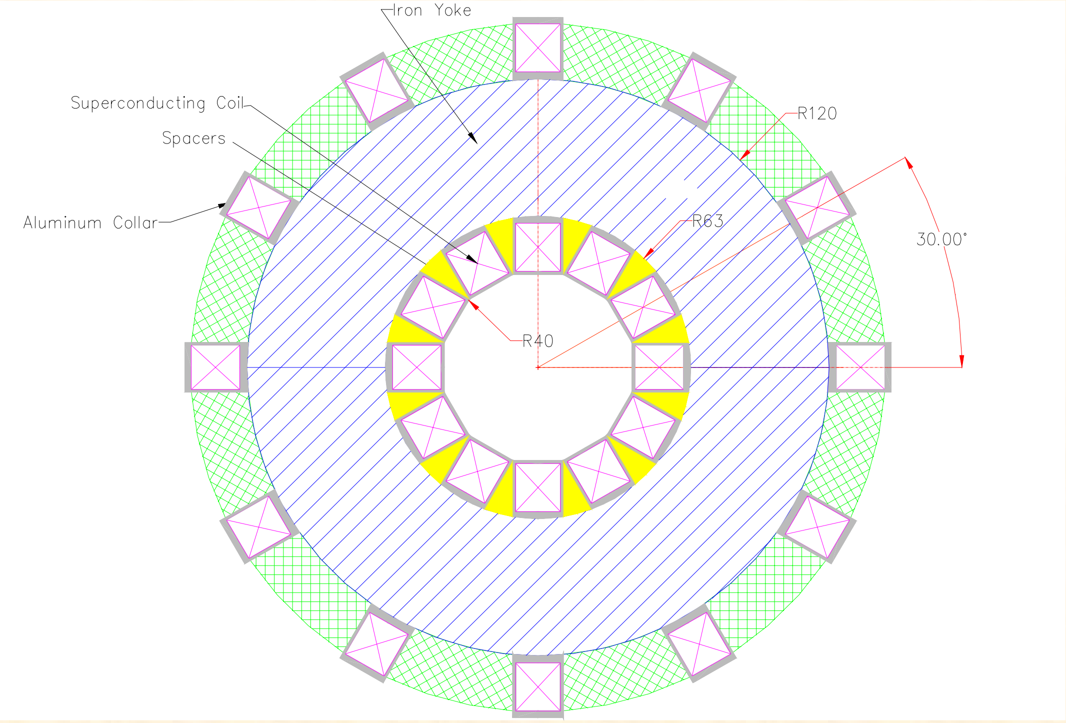
- Coil cross section (X1 & X2 configuration)



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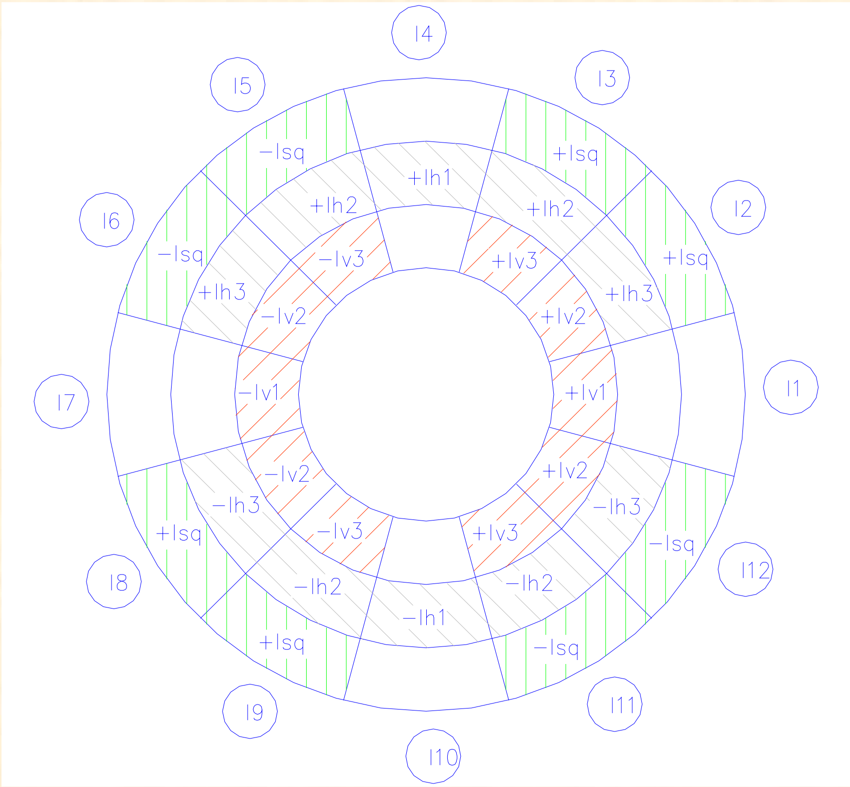
"Current Algebra" for Flat Coil



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- Example of powering configuration – X1

$$
\begin{aligned}
I_1 &= I_{v1}\\
I_2 &= I_{v2} + I_{h3} + I_{sq}\\
I_3 &= I_{v3} + I_{h2} + I_{sq}\\
I_4 &= I_{h1}\\
I_5 &= -I_{v3} + I_{h2} - I_{sq}\\
I_6 &= -I_{v2} + I_{h3} - I_{sq}\\
I_7 &= -I_1\\
I_8 &= -I_{v2} - I_{h3} + I_{sq}\\
I_9 &= -I_{v3} - I_{h2} + I_{sq}\\
I_{10} &= -I_4\\
I_{11} &= I_{v3} - I_{h2} - I_{sq}\\
I_{12} &= I_{v2} - I_{h3} - I_{sq}
\end{aligned}
$$

I_{v1}, I_{v2}, I_{v3} – vertical dipole currents

I_{h1}, I_{h2}, I_{h3} – horizontal dipole currents

I_{sq} – skew quadrupole current

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Flat Coil Array Summary

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- Advantages
  - One assembly (with possible 15° rotation for sextupole) for all required corrector configurations
  - More flexible operation possible
  - Fewer spares needed
- Challenges
  - New approach - R&D needed
  - Field errors somewhat larger
  - More power supplies required; current imbalances must be corrected; programmed power supply control algorithms needed
  - Larger radial space needed

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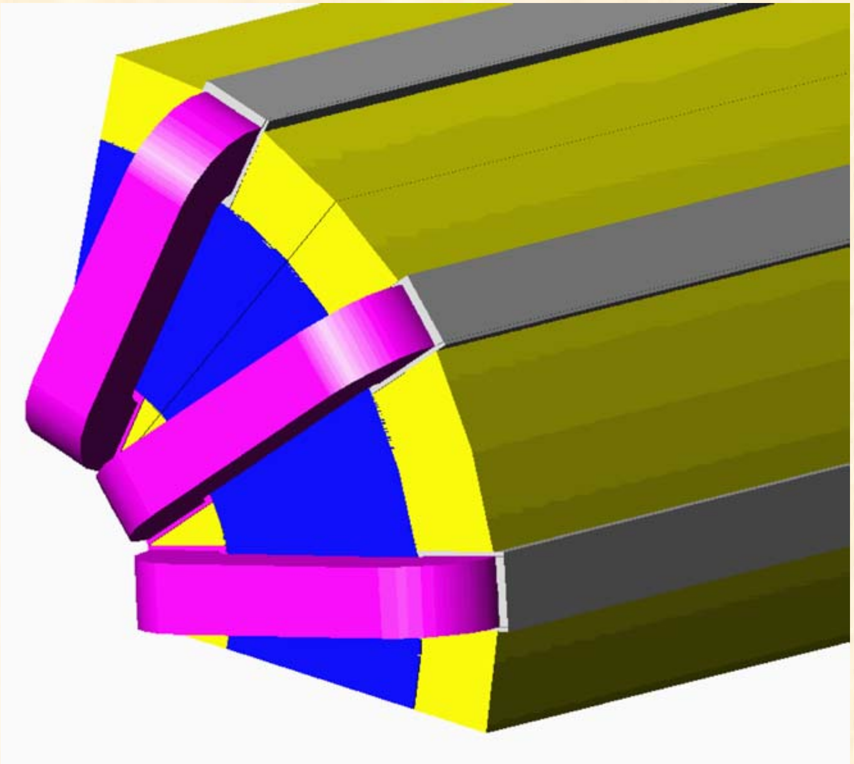
Flat Coil Array R&D



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- Development plan
  - Fabricate 3 coil ("1/4" array) assembly
  - Study mechanics, assembly, and limited powering regime
  - Extend to full array ?
  - Funding and schedule limited: need decision on corrector design by Q1 FY 2005

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Corrector Design Summary

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- Baseline cos ($n\theta$) approach meets requirements
  - Field strength
  - Field quality
  - Conventional design most similar to LHC correctors
  - Uses less radial space
  - No significant development
- Alternative flat coil approach
  - Meets requirements
    - Field quality needs a little examination
  - Provides significant flexibility
  - Requires a development program
  - Schedule is a major issue

HTS Leads

- HTS Leads are required for the new 10kA low beta quadrupoles due to refrigeration limits
- Fermilab has installed one 6kA HTS spool in the Tevatron and has three other HTS spools
- Baseline is to use a pair of 6kA leads in parallel to provide the 10kA requirement
  - Vendor has indicated that they can re-produce existing design
  - Leads are well understood from extensive R&D program at Fermilab
  - However this doubles the number of leads to be accommodated in the system

HTS Leads

- Cost and schedule prohibit a development program for new 10kA HTS leads
- Alternative approach - use existing lead design and 'over cool' to reach 10kA
  - During R&D phase >7kA reached during testing
  - Limiting element may be conventional section (Cu)
  - It might be possible to modify slightly the Cu section without affecting the HTS section (and keep the cost finite…) or they might work in over cooled state
- Test of existing H-spool to explore current limits (in preparation, S. Feher)

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6kA modified H-Spool Test

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- **TSHH-296 6kA HTS lead spool to be tested in MTF**

HTS Leads Summary

- HTS leads required by refrigeration constraints
- Baseline design uses pairs of 6kA leads to meet the 10kA requirement
- Test in preparation to explore higher current operation of 6kA leads with additional cooling
- Only a two vendors exist who can meet our requirements including cost and schedule: no significant R&D is possible

A Possible Procurement Plan

- Correction Coils (baseline approach)
  - Two vendors for cost control, security
  - Cold test (quench) capability
- HTS Leads
  - Single vendor
- Final Assembly
  - Single vendor
- Fermilab
  - Intermediate component testing
    - Magnetic measurements
    - HTS leads cold tests
  - Final alignment, harmonics, and cold testing of completed spools

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Summary

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- Overall design is proceeding well
  - Concepts are developed
  - Most components are based on existing designs
  - Details to be decided in a timely manner
    - Cryogenic interfaces
    - Bus design
- Critical component decisions to be resolved:
  - 10kA HTS leads – 2 pair baseline or 1 pair ‘over cooled’
    - Number of qualified vendors an issue
  - Corrector magnets – cos ($n\theta$) baseline or flat coil array with some development
- Number of qualified final assembly vendors an issue
- Schedule will be ultimate driver – little ‘float’ with funding not beginning until FY2005
  - Little or no time for (R&)D